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CALCULATION OF UNSTEADY FLOW IN LONG FREE-FLOW PIPELINES OF WATER SUPPLY NETWORKS

Abstract. St. Venant equations were used to calculate response time parameters of water distribution system, containing parts with gravity flow, which change the performance of pumping stations. It is shown that this time can, in some cases up to 10–20 minutes, which should be taken into account in the development of algorithms for automatic control of pumps.

Keywords: water distribution system, gravity flow, St.Venant equations, response time.

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РАСЧЕТ НЕСТАЦИОНАРНОГО ТЕЧЕНИЯ В ДЛИННЫХ БЕЗНАПОРНЫХ ТРУБОПРОВОДАХ СЕТЕЙ ВОДОСНАБЖЕНИЯ

Аннотация. С помощью уравнений Сен-Венана произведена оценка времени реагирования параметров сети водоснабжения с участками безнапорного течения на изменение производительности насосной станции. Показано, что это время может в некоторых случаях достигать 10–20 минут, что следует учитывать при разработке алгоритмов автоматического управления насосами.

Ключевые слова: сеть водоснабжения, безнапорное течение, уравнения Сен-Венана, время отклика.

Water supply network is a part of the infrastructure of any more or less large settlement. Its smooth functioning and proper regulation is vital. Networks operate under conditions of unregulated water consumption. It is necessary to ensure there is a guaranteed supply of water to consumers in case of possible peak loads and any failure of system elements. It is also needed to provide an economically feasible modes for low load periods. Make informed technical decisions on reconstruction and expansion of networks, to perform the operational management of water distribution, taking into account a variety of factors (including random) that affect the network. It is impossible without the computer calculations using hydraulic models.

All the problems arising during the modeling of water supply and sanitation, in terms of hydraulics can be divided into four groups:

— stationary flows in pressure pipelines;

— unsteady rapidly changing transient flow in pressure pipelines;

— stationary open-channel flow in sewerage networks;

— unsteady flow in slowly changing sewerage networks.

The tasks of each group describe their mathematical relations. In the first case it is the balance equations and the mechanical energy consumption in an integral form; in the second — a system of differential continuity equations and Navier-Stokes equations. Stationary gravity flow is calculated using ordinary differential equations uneven flow, and in simple cases even with the help of the equation Chezy. The most difficult task is related to the fourth type, which arises during for the solution of the system of unsteady differential equations of St. Venant (“shallow water” equation).

Different software is used to solve these problems. However, engineering experience shows that standard approach fails in the case under consideration. One of these problems is discussed below.

During the work on the reconstruction of the pumping station water supply system in one of the cities of the Sverdlovsk region, it was necessary to identify some dynamic characteristics of the network as an object of regulation.

Taking into account the requirement to determine the response time of the network parameters (delay), when operating mode of the pump changes, it is essential to develop of the control algorithm.

We have developed the mathematical model of the network, through which its work is analyzed at steady and unsteady conditions. The configuration of the simulated network is given in Fig. 1.

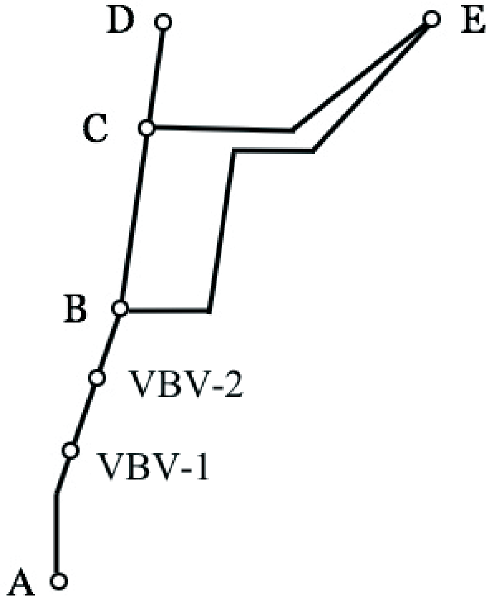

Fig. 1. The configuration of the simulated network

The topology of calculated network scheme is simple. The pumping station is located in the junction node *A*. Water is pumped into two parallel pipes with the length of about 14 km and the diameter of 1000 mm to junction node *B*. Pipelines laid in steep terrain. The difference in height along their length is up to 72 m. In order to avoid a vacuum inside the conduits on them several vacuum breaking valves (VBV) are installed on them. The water is supplied by one pump and the flow is approximately 3000 m^3/h. Water demand between points *A* and *B* is absent.

All consumers of this zone are located beyond the point *B*. Their water demand is not more than 35 %. The rest flow goes to the open reservoirs (junction node *E*), from which the water is supplied to other parts of the city. Regulation of the pump is carried out by the pressure at junction node *C*.

Observations show that the change of hydraulic head during a day in the network is typically (Fig. 2). Maximum head is observed at minimal water demand (night and early morning); increase demand during the day and evening leads to its reduction.

The important point is that the pressure and flow of the pump with a constant speed of the shaft rotation are unchanged, which is confirmed by special studies. The water level in the reservoirs (node *E*) varies within half a meter, i. e. it is sufficiently stable and does not exert any significant effect on the parameters of the network.

At node *C* it is necessary to maintain the pressure of about 40 m. At the existing conditions it is only possible with the help of regulating valves pumping station. Observations showed, that the pressure change in the node *C* become apparent only after 15–20 minutes after changing the position of the regulating valves. Explanation of this phenomenon in the traditional approach is not possible.

In order to achieve the adequacy of the model head was measured at certain points in the network and the flow in some pipes. Using these data, we performed a calibration of the model. It helped us to clarify the hydraulic resistance of pipelines and the value of node demands.

Fig. 3 shows the calculated hydraulic grade line (HGL) for circuit pipes *A-B-C-E* (Fig. 1), corresponding to the average water demand. It can be seen, at VBV-1 (the highest point), where an air valve is installed, hydrostatic head coincides with the elevation, i. e. valve is

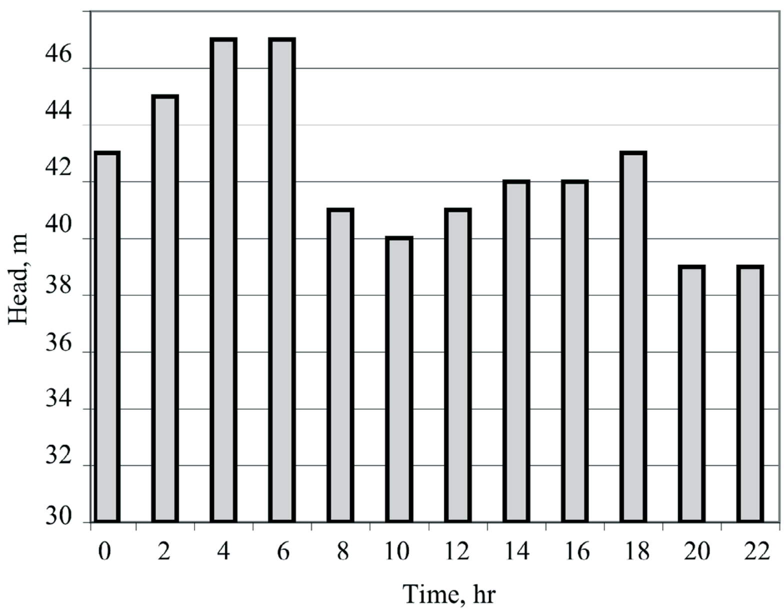

Fig. 2. Hydraulic grade during a day in the junction node *C*

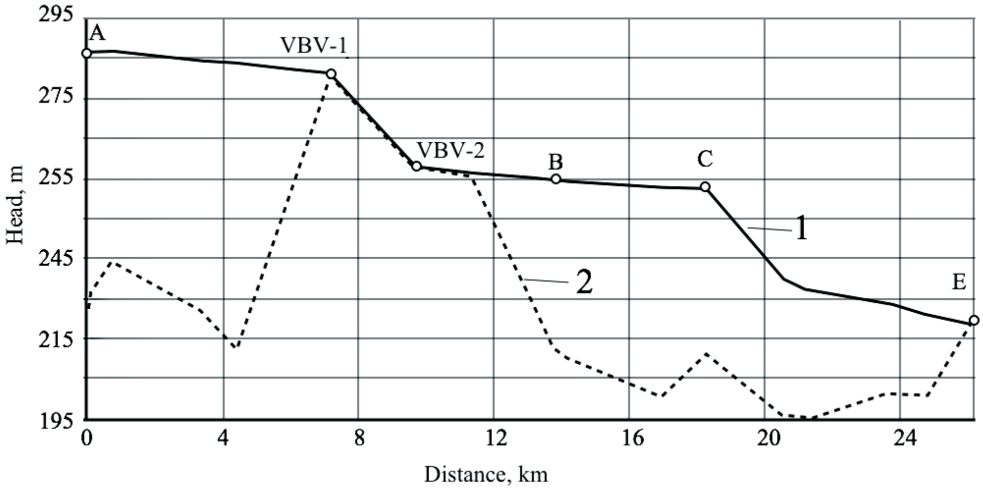

Fig. 3. Hydraulic grade line (1) and elevation nodes (2) for circuit pipes *A-B-C-E*

open. Calculations performed based on daily water consumption unevenness demonstrated that overpressure in node VBV-1 is absent in all modes of operation of the network. The calculations also showed that at distance about 2.5 km between valves VBV-1 and VBV-2 there should be gravity-flow. Modeling of the flow when changing the pump mode (for example, when the position of the regulating valve) is not possible with traditional methods.

We used a system of St. Venant equations in one-dimensional formulation. For the calculation of the flow:

$$\frac{\partial Q}{\partial x} + \frac{\partial (S + S_0)}{\partial t} = 0,$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(\frac{\beta Q^2}{S} \right)}{\partial x} + gS\left(\frac{\partial y}{\partial x} + i + i_f \right) = 0$$

where Q — flow, S — active cross-sectional area of flow, S_0 — inactive cross-sectional area of flow, y — flow depth, i — slope of pipe, i_f — friction slope, β — coefficient for nonuniform velocity distribution in cross-section, g –acceleration of gravity.

Calculations were carried out for the flow in the circuit VBV-1– VBV-2 — *B*, using the software and the method described in [1]. In order to determine the response time of the system to change at the operating mode of the pump to the input of the simulated pipeline the feed stream with variable flow and calculates its variation along the length of the circuit. The simulation results are shown in Fig. 4.

It can be seen in the section VBV-2, located at a distance of 2.5 km downstream from VBV-1, flow reduction starts after about 12 minutes after a disturbance in section VBV-1. Section *B* is located at the distance of about 6 km from VBV-1. At this point the flow change begins at about 22 minutes after reducing flow. Downstream from the section *B* flow is always under pressure, so the spread of the parameter variation occurs almost instantly. These assessments of network response time to changes in pump performance are very close to the observed values.

Conclusions

1. With the help of the St. Venant equations calculated response time parameters water distribution system, containing parts of gravity flow, changing the performance of pumping stations.

2. It is shown that this time can, in some cases up to several tens of minutes, which should be taken into account in the development of algorithms for automatic control of pumps.

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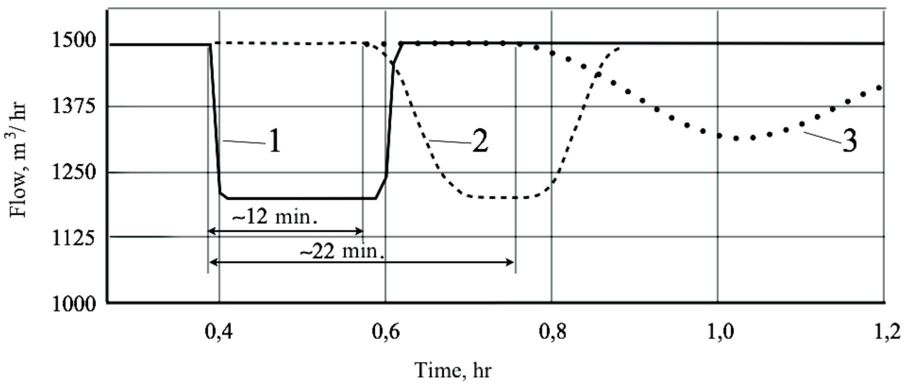

Fig. 4. The flow variation of the length of conduit: 1 — section VBV-1, 2 — section VBV-2, 3 — section *B*